SIMULATOR ADAPTATION SYNDROME LITERATURE REVIEW

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1 INTRODUCTION

The following review of literature was performed in support of a Small Business Innovative Research (SBIR) contract with the United States Army Tank-Automotive and Armaments Command (TACOM). The project is titled “Integrating a Motion Base into TARDEC’S CAVE Automatic Virtual Environment.” The selection of topics for review was based on discussion and results from the Phase I and Phase I Option periods of the project as a CAVE-based ground vehicle driving simulator was developed. In addition, a general search of issues pertaining to simulator sickness, driving simulation, motion cueing, virtual reality, display systems, and general application of virtual environments was performed. Relevant findings are discussed in this document.

The following sections include a general discussion of simulator sickness issues and how various driving simulator configuration options might affect the occurrence and severity of symptoms. It is assumed that the reader will have at least an intermediate knowledge of the application of virtual environments and driving simulation. In general, a topic area will be defined or explained, then a discussion of how the information from the literature may be applied to this program.

2 THE SIMULATOR SICKNESS ISSUE

Simulator sickness or the report of ill feelings associated with the use of simulation devices has been around for a long time. Casali (1986) noted that documentation of simulator sickness can be found in reports by Havron and Butler as early as 1957 in a helicopter flight training simulator. In these early reports, the phenomenon was reported as motion sickness or the result of exposure to low frequency, whole body motion. Both motion sickness and simulator sickness can result in an array of symptoms including eye strain, headache, postural instability, sweating, disorientation, vertigo, pallor, nausea, and vomiting.

Although the symptoms are common between motion and simulator sickness, they are not necessarily the same thing. Casali (1986) makes the distinction based on research conducted by Money (1970) that stimulation of the vestibular system is required to induce motion sickness. However, there are many reports of simulator sickness and related symptoms in fixed-based simulators that include no physical motion cues. Therefore, it appears that it is beneficial to draw a distinction between motion and simulator sickness because it is not only the actual physical motion that can cause sickness. It appears that some result of visual processing, likely perceived motion or vection, can also be a contributing factor in the incidence of simulator sickness (Kennedy, Hettinger, and Lillenthal, 1988). Indeed, there are a number of factors that contribute to simulator sickness, a fact that led Kennedy and Fowlkes (1992) to describe simulator sickness as a syndrome because it has many complex contributing causes and manifests itself with many potential symptoms. A good discussion of contributing factors can be found in Kolasinski (1995). A similar format will be used to discuss these factors and how they relate to simulator sickness and performance validity in the CAVE.

The consequences and implications of simulator sickness on the validity of simulation can be severe if not controlled and accounted for (Casali, 1986). Many of today’s driving simulators are used to perform research, training, or proof of design activities. A prerequisite to generalizing the results found in research conducted in a simulator is an understanding of the validity of the resulting experience. Without question, simulator sickness is a factor that has an impact on the

validity of results from research simulators. Simulators can affect an operator's performance in a variety of negative ways due to inappropriate behaviors, loss of motivation, avoidance of tasks that are found disturbing, distraction from normal attention allocation processes, and a pre-occupation with the fact that something is not quite right. Given the potential consequences of simulator sickness, it is difficult to assess the value of results obtained from a simulator known to cause significant sickness problems.

In addition to problems with validity, there is potential danger due to lingering reactions long after the simulation experience. Blurred vision, postural instability, nausea, and general discomfort are the types of lingering symptoms that can be experienced. Kennedy, Fowlkes, and Lilienthal (1993) identify that the most dangerous potential aftereffects are disturbances in locomotor and postural control. These effects can last for hours or potentially much longer. Care must be taken by simulation users to understand the impact of simulation exposure on the operator and protect them from potential danger.

Hettinger and Riccio (1992) indicate that performance effecting simulator sickness is most likely to occur in initial exposures to a simulator, particularly when there are high rates of optic flow and frequent changes in acceleration. This creates a huge challenge for creators of driving simulation systems where large optic flows and frequent acceleration changes are a necessary component of the simulated task. Given there are major consequences associated with simulator sickness in driving simulators, it is important to understand the underlying mechanisms and processes that bring it about. A thorough understanding should allow for better design decisions or breakthroughs in novel techniques to help reduce simulator sickness. The following section provides a brief explanation of the visual and vestibular systems to provide background for a better understanding of the physiological mechanisms associated with simulator sickness.

3 THEORIES OF SIMULATOR SICKNESS

There are several theories behind the concept of simulator sickness. The three most prominent theories will be presented here. They include cue conflict theory, poison theory, and postural instability.

3.1 CUE CONFLICT THEORY

Cue conflict theory is the primary theory used to describe the etiological processes that occur with simulator sickness. The main premise of the theory is that sickness occurs due to mismatches between what the sensory systems expect based on previous experience and what actually occurs in the simulator. The mismatch causes internal conflict that cannot be resolved and eventually results in the symptoms associated with simulator sickness. An example of this conflict can be found in a fixed-based simulator where visual cues are presented to indicate linear acceleration but since the driver is not actually moving, no corroborating vestibular cue is detected. Drivers of real vehicles have learned to expect that with visual cues of acceleration there will also be a corresponding vestibular cue of acceleration. Therefore, a conflict will be detected and simulator sickness could result.

There are a number of types of cue mismatch that can lead to cue conflict in driving simulators but the most salient is between the visual system and the vestibular system. The coupling between the visual and vestibular sensory systems is quite close given their importance to processes of spatial orientation and the rapid exchange of information required to support

balance and locomotion. In a ground vehicle simulation application, appropriate cueing for sensation of motion can be a primary factor in the success of the simulator.

There does appear to be some relationship between level of experience with the real world task and incidence of sickness seen while performing the task in a simulator (Pausch, Crea, and Conway, 1992). The more experience an operator has, the more likely they are to experience symptoms. This supports cue conflict theory in that the more intimate the operator is with the types of sensory responses they should be receiving, the more likely they will be to either consciously or unconsciously recognize when something doesn't quite match.

An important finding in motion sickness research is that a necessary requirement for experiencing sickness is a working vestibular system (McCauley and Sharkey, 1992 reviewing Howard, 1986). Theoretically, the addition of a motion system to provide surrogate cues to the vehicle's acceleration should help reduce the amount of mismatch and therefore reduce simulator sickness. However, previous efforts to add motion cueing to simulators have not always produced the desired results. Some reports indicate that the addition of motion cueing has reduced sickness (Casali, 1986; Currey, et al. 2002;), while others report no discernable differences (Sharkey and McCauley, 1992; Barnes, 1987; Kennedy, et al. 1993). The absolute success or failure of using physical motion cues to reduce cue conflict does not appear to have been determined as of yet.

Even though cue conflict theory is the most widely accepted theory of simulator sickness, there are several problems with it that have lead some to question it's viability as an explanation for simulator sickness (Stoffgren and Riccio, 1991). The first issue is that the theory does not allow for effective prediction of simulator sickness. There is no reliable formula based on sensory inputs and conflicts that can be used to determine which situations will produce sickness and which will not. Second, according to the theory, lack of cue redundancy is a major determinant of when sickness will occur. However, there are many instances in our environments where sensory cueing is not redundant and we don't get sick. Therefore, lack of cue redundancy cannot be a predictive factor in simulator sickness. Third, there is no explanation for why the simulator sickness is prevalent at first exposures and then will tend to disappear after repeated exposure. Last, there has been no explanation why cue conflict will result in nauseogenic response. There are not know neural processing centers that would account for such a response and it is unlikely that there is an undiscovered neural processing center that is dedicated to this particular response.

Even with its potential drawbacks, the cue conflict theory of simulator sickness does tend to support the available experimental data fairly well and remains the most widely accepted view.

3.2 POISON THEORY

The poison theory attempts to explain simulator sickness from an evolutionary point of view (Treisman, 1977). With this theory, it is believed that the types of sensory stimulation artifacts found in virtual environments such as blurred vision, temporal instability, and lack of sensory coordination are similar to the symptoms one experiences as a result of poison or intoxication. One of the body's most automatic responses to poison includes vomiting to empty the contents of the stomach. There the premise of this theory is that the effects of virtual environments lead the body to believe that it has ingested poison and the body reacts to rid itself of the problem. As with the cue conflict theory, there are also problems with the poison theory. There is no way to predict when or how fast individuals will elicit this response. There is also no explanation as

to why some individuals are affected more than others, especially in the case of experience with the real world task. Due to these limitations, it is hard to verify or validate this as a viable theory.

3.3 POSTURAL INSTABILITY

The postural instability theory of simulator sickness was developed as an ecological alternative to cue conflict theory. The theory is centered around a premise that the sensory systems are constantly attempting to maintain postural stability in our environment. Postural stability is a state where uncontrolled movements attempting to correct perceived variance from normal postural state are minimized (Riccio and Stoffgren, 1991). So our perceptual and action systems are continually attempting to maintain our postural stability in our environment. Sickness occurs when an individual is attempting to maintain stability under a set of environmental conditions when they have not yet learned strategies for accomplishing the task. In support of this theory, Stoffgren and Riccio argue that postural instability both precedes sickness but is also necessary to produce symptoms. There is no explanation for how the lack of postural stability ultimately results in an emetic response but does provide some basis for the diminishing effects of sickness as the individual learns the environment.

Although none of the competing theories fully explain the simulator sickness phenomenon, we can take a conservative approach to simulation design by working to accommodate each as we make simulator design decisions.

4 THE VISUAL AND VESTIBULAR SYSTEMS

The visual and vestibular systems are of primary concern when considering the human sensory systems that are involved with simulator sickness. The relevant aspects of each are described in the sections below.

4.1 IMPORTANT ASPECTS OF THE VISUAL SYSTEM

The visual system is a very complex and heavily researched sensory system. It is not within the scope of this document to provide a full description of the anatomy and processing that makes up visual perception. Other reference materials such as Goldstein (1989) provide good explanations of the visual system. Within the scope of this document, it is important to understand key characteristics of the visual system. Therefore, these characteristics will be discussed in the following paragraphs.

4.2 CENTRAL VS. PERIPHERAL VISION

Much of the following discussion was derived from Goldstein (1989).

Light energy entering the eye through the pupil is focused on the retina. The retina is essentially the interior surface of the eye and is, for the most part, a mosaic of receptors that produce stimulus in response to light. There are two types of receptors that make up this structure, the rods and cones. The cones are primarily responsible for perception of color and for seeing fine detail, are densely packed into small region of the retina called the fovea. The rods, which are much more sparsely distributed over the remaining portion of the retina, are responsible for vision under conditions of low illumination. As our eyes move to pick up a target

to view, they are working to focus the target image on the retina within the area of the fovea. The resulting area of perceived vision has been referred to as central vision. The surrounding area is not well adapted for seeing specific targets but is good at detecting moving objects and plays a part in the perception of self motion. The perceived vision from this are is called peripheral vision (Leibowitz, 1986).

The receptors responsible for central vision are good at maintaining a sustained response which means they will continue to fire as long as the stimulus is present. This has several implications for how this eye must function and what central vision is good for. Because the receptors fire as long as the stimulus is present, they are well suited for detail and pattern matching types of perception. It must also be true that the image must be stabilized for some period of time while the perceptual processing occurs in order to support the sustained response. These properties correspond well with our understanding of how the eye moves as we look at target objects. Movements of the eye consist of saccade, smooth pursuit, vestibule-ocular reflex (VOR), optokinetic reflex (OKR), and vergence. All of these movements except for the latter are associated with stabilizing an image in central or foveal vision. Of these eye movements, VOR and OKR are of particular interest when considering the effects of virtual environments and resulting simulator sickness and they will be discussed later in further detail.

Peripheral vision has been thought to be responsible for our perception of motion. The receptors outside the fovea are much better suited for detecting transient stimulus and will fire as they detect a stimulus but will not continue to fire. Therefore, the peripheral sensors are sensitive to moving objects and also changes in orientation of the individual. Information about changes in orientation is believed to feed back into part of the brain that determines posture, balance, and self-motion acting almost as a proprioceptive sense. A summary from Money (1983) summarizing Leibowitz and Dichgans (1980) below shows the key features of the central and peripheral vision:

Table 1. Summary of Peripheral and Central Vision Features

Central Vision	Peripheral Vision
Serves to answer the question “what”	Serves to answer the question “where”
Small stimulus patterns, fine detail	Large stimulus patterns
Image quality and intensity are important	Image quality and intensity are not important
Central retinal area only	Peripheral and central retinal areas
Well represented in consciousness	Not well represented in consciousness
Serves object recognition and identification	Serves spatial localization and orientation

Changes in the location of objects in peripheral vision over time provide information about how an observer is moving through their environment. One of the key affect associated with this phenomenon is called optic flow. Optic flow will be discussed in the following section.

5 OPTIC FLOW

Optic flow is created by the movement of elements in the optic array that occur as an observer moves relative to their environment (Goldstein 1989). A simple example of this can be found as you ride in a vehicle and you fix your gaze in the direction you are traveling. All objects within the field of view will appear to move away from the center of your destination or point of

expansion (POE). Figure 1 below illustrates the directions that objects will appear to move as you move through the environment.

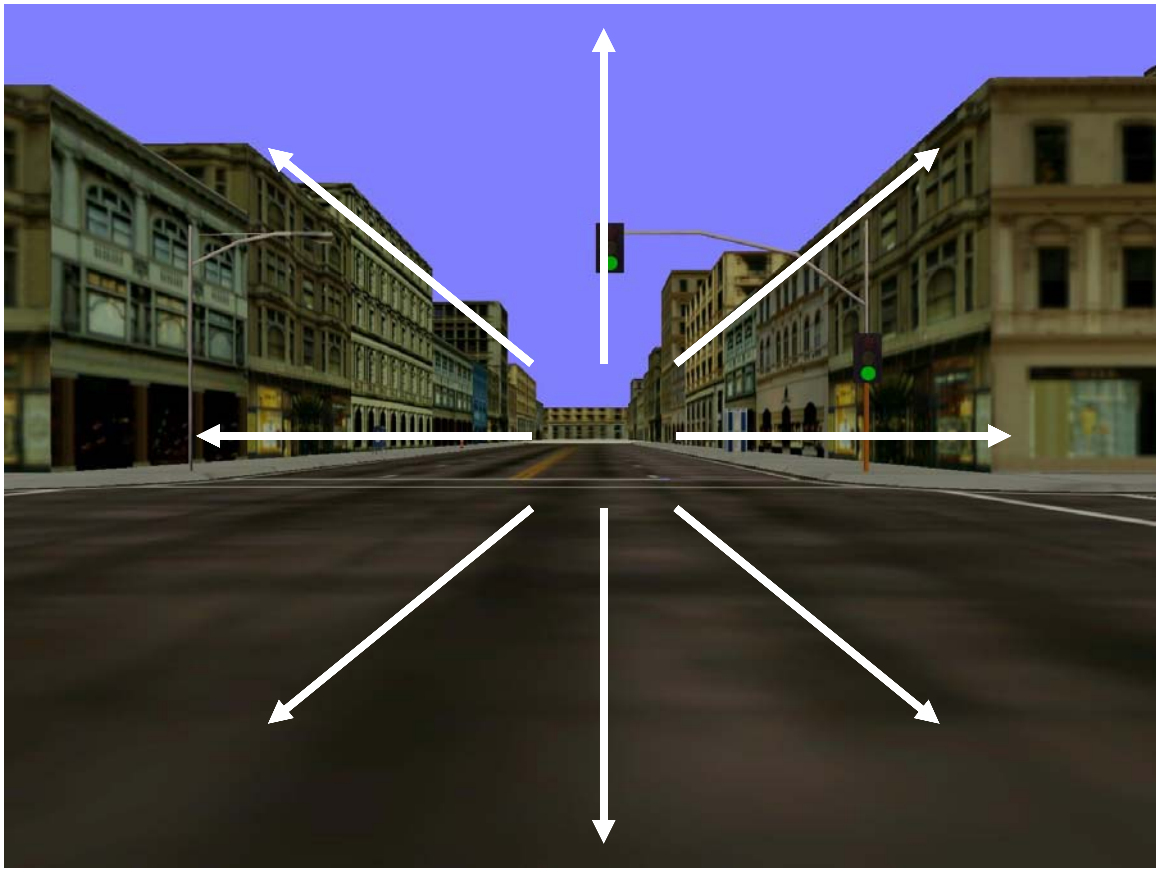
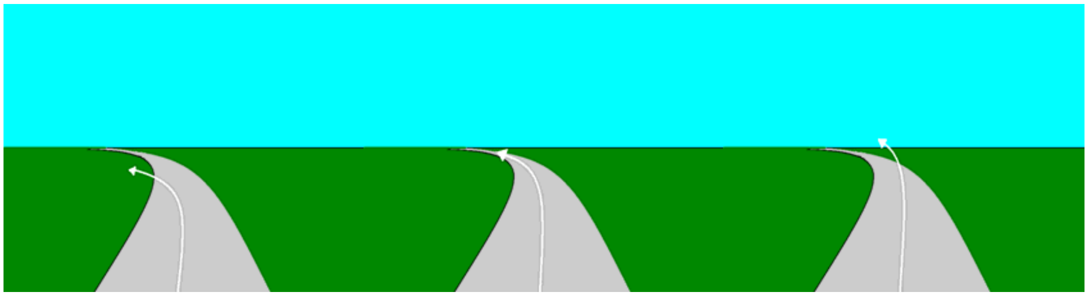


Figure 1. Optic Flow Example

Gibson first proposed that the optic flow is a major source of information that we use to determine where our current direction of travel will take us. The POE, he hypothesized, is an invariant source of information that lets us know where we are headed. However, others have pointed out that in tasks such as driving a car, drivers often look at the center line or edges of the road and the end destination may not even be in sight. In other words you can know you are traveling towards a target while looking off angle or elsewhere in the world. Therefore, there is no guarantee that the POE is being used to determine motion towards a target.

An expanded notion of how the optic flow is used indicates that some other feature of the optic flow besides the POE is being used. With this theory, it is hypothesized that drivers perceived a locomotor flow line based on how objects are moving directly beneath the driver. Perception of this line allows a driver to predict where the vehicle will be in the future by extending the locomotor flow line. Figure 2 below illustrates this effect. This theory better explains how we are able to move through our environment without direct visibility to the POE and why drivers tend to make use of information received by looking at the center line and road edges.



Error Inside Road Path On Target Error Outside Road Path

Figure 2. Locomotor Flow Lines

The optic flow also provides information about our speed relative to the environment. The faster more rapidly objects move along the flow lines, the faster the observer perceives their motion. Human perception of changes in optic flow appears to be quite sensitive and often occurs without conscious thought or effort. It is this sensitivity that requires driving simulation developers to take special care when considering design trade-offs to faithfully reproduce this effect in any display of visual motion information.

5.1 PERCEPTION OF DEPTH

Our perception of depth comes from a number of sources including oculo-motor cues, pictorial cues, motion-produced cues, and binocular disparity. The oculo-motor cues are those given by the position of our eye and tension on the muscles within the eye. Pictorial cues are those that could be extracted from a still picture. Motion-produced cues depend on the motion of the observer or the objects in the environment. Binocular cues come from the fact that slightly different scenes are formed on the retina of our eyes. Each of these cues will be discussed in the following paragraphs.

The oculo-motor cues include convergence and accommodation. Both operate by giving proprioceptive feedback to the brain about where an object is that is being focused on. Convergence is the inward angular positioning of the eyes to keep an object focused on the fovea as the object is moved closer to the observer. The closer the object to the observer, the greater the muscular input is required to keep it positioned on both fovea. Accommodation is the process of flexing muscles in the eye to change the shape of the lens as an image is brought into clear focus on the retina. The closer the object, the more muscle tension is required to bulge the lens of the eye. These effects typically only occur when the target object is within a distance of 5-10 feet. Objects further away are normally focused without any adjustments to the orientation of the eyes.

The pictorial cues include size of retinal image, familiar size, interposition, height in field of view, atmospheric perspective, and linear perspective. The size of retinal image can help determine size and is somewhat related to the cue of familiar size. In general, interpret larger objects to be closer than smaller objects. There is an interaction of course with our expectation of how large the object should be. If the retinal image of an object is very small and the retinal image of another identical object is much larger, we perceive the object with the smaller retinal image to be further away. Likewise, because we know from our past experiences about how large an object such as a car might be. We can draw some inference as to how far away it is due to the

disparity between how large we know the object to be when we are close compared with the size of the object in its current position.

Interposition is a very simple yet very compelling cue to depth. If there are two objects in a scene and one of the objects is cover part of the other. The object being covered is perceived to be further away.

The height in the field of view also provides information about depth. In a typical outdoors scene the horizon line might be considered the middle of our vertical field of view. Objects that are closer to the observer are lower in that field of view where object that are higher are perceived to be further away. For example if a rabbit is seen at the very bottom of the observer's vertical field of view, it will be interpreted as being close to the observer. If it is in the middle of the field of view, say at the horizon line or so, the rabbit will be perceived as being much further away.

Atmospheric perspective is a cue driven by the fact that objects closer to an observer are much sharper in appearance due to less interference from dust, humidity, and other particles suspended in the air. In addition, the closer an object is the greater the amount of detail is available as to the objects texture and shape.

Linear perspective is a pictorial cue in which lines that are parallel in a scene such as lane marking edges are seen to converge as they go further and further away from the observer. Therefore, depth information about objects that are placed next to the converging line can be extracted by evaluating relative position along that line.

Motion-produced depth cues include motion parallax and accretion and deletion. As an observer moves through an environment, objects that are further away appear to move slowly in the direction of the observer's movement. Closer objects appear to move more rapidly in the direction opposite the observer's movement. The apparent angular velocities of the objects will be inversely proportional to their distance from the observer. Accretion and deletion are related to motion parallax and interposition. If two surfaces are at different distances from the observer, any movement in the observer that causes one surface to cover another will give cues to depth. The covering surface is seen to be closer then the covered surface.

Binocular disparity is perhaps one of the most important cues to depth. The individual eyes see the world as two slightly different pictures due to the slightly different vantage points created by the distance between them. The brains ability to fuse these disparate images into a single visual image produces strong perception of depth. It is this capability that has been exploited to develop stereo displays. Stereo display devices have been around since the early 1800s and have more recently been adapted to computer generated graphics rendering systems.

5.2 OPTO-KINETIC REFLEX

Opto-kinetic reflex (OKR) is one of several eye movements that function to identify a target in visual scene, to position the target on the fovea, and to keep it positioned there. The OKR works by evaluating information from the entire retina to determine if image slip is occurring. If there is an image slip, a corresponding movement is made in the eye position to eliminate it, thus stabilizing the image. An example of this process at work is when we look out the window of a vehicle. As the reflex detects slippage in the image, it applies a compensating movement to the eye with a gain equal to the motion and direction of the optic flow.

There is another similar reflexive response that is caused by changes in head orientation detected by the vestibular system called vestibular-ocular reflex (VOR). The opto-kinetic reflex and the VOR are involuntary responses that work synergistically to produce a stable retinal image under a variety of dynamic viewing and motion conditions. A brief discussion of how these reflexes work together is given in a later section of this report.

6 IMPORTANT ASPECTS OF THE VESTIBULAR SYSTEM

Much of the following explanation is taken from Draper (1996), LaViola (2000) and Nehrenz (2000). The vestibular system is designed to detect and react to the position and motion of the head in space. As a sensory system we are hardly aware of its function. Even though we are not aware of this system, its correct function is critical to our ability to coordinate motor function, produce correct eye movements, and maintain correct posture. We are typically only aware of this system when we experience a disruption in its function such as what might occur with certain diseases or acute conditions such as motion sickness.

There are two divisions in the inner ear that include a complex set of mechanisms that allow us to hear and sense motion. Functionally divided, the mechanisms are the cochlea which is associated with the sense of hearing and the peripheral vestibular system is associated with balance and sense of motion. The peripheral vestibular system rests in an area of the inner ear called the labyrinth. It is made of up a series of tubes (semicircular canals) and sacs (utricle and saccule). The semicircular canals are primarily responsible for detecting angular acceleration while the utricle and saccule are responsible for linear acceleration.

The three semicircular canals are oriented to detect motion in each of the three planes in which motion can occur. Each canal detects motion in a single plane. These mechanisms are suspended in a fluid called perilymph and are filled with a fluid called endolymph. As the head moves, the endolymph within the tube flows causing the tiny hairs to bend generating nerve impulses. The nerve impulses are then transmitted to the brain through the vestibular nerve (Eighth nerve). The semicircular canals are quite sensitive and can measure angular accelerations as low as 0.1 deg/s^2.

The utricle and saccule work through similar processes. The hair-like cilia of these organs are embedded in a gelatinous mass. The gelatinous mass has clumps of crystals called the otolith. When linear acceleration occurs, the otolith provide enough inertial to flex and stimulate the cilia. The stimulation results in the generation of nerve impulses that are then transmitted to the brain. The utricle is oriented to be able to detect motion in the horizontal plane and the saccule is oriented to detect motion in the vertical plane and fore-aft plane. These receptors are primarily responsible for our perception of vertical orientation with respect to gravity.

Once the brain receives the impulses from the entire vestibular system, it uses the information for perception of motion and also transmits information to the visual system. More discussion of this process will be included in the following sections.

6.1 VESTIBULO-OCULAR REFLEX

There is a clear relationship between the vestibular and visual systems where angular acceleration information about head movement is supplied to the visual system. The visual system interprets this information and makes a corresponding eye movement to stabilize the

visual image on the retina. The process is called vestibulo-ocular reflex (VOR). A simple example of this effect can be shown by holding a piece of paper with some printed text in front of your eyes. If you should shake your head around while holding the paper stationary, you are able to read the text with some level of effort. If you hold your head stationary and shake the paper around, it is much more difficult or impossible to read the text. When the head moves, the vestibular system is providing information to the eyes allowing them to stabilize the image of the shaking paper on the retina. In the case where the paper was moving, there was no information about how the paper was moving that could be sent to the eye and the image could not be stabilized.

The VOR and the optokinetic reflex (OKR, as discussed earlier), work together synergistically to maintain a stable retinal image regardless of the type of motion being experienced (Zacharias and Young, 1981). The VOR is a very fast acting reflex that serves to compensate for head movements in the 1-7 Hz range. However, the VOR is much less accurate at lower frequencies and has less than perfect gain. The OKR has the opposite performance characteristics. It has a longer latency due to the required evaluation of visual information to determine a response and has near unity gain at low (<.1 Hz) frequencies. Between .1 and 1 Hz frequencies, the OKR begins to lose gain and also develops a phase lag due to inherent response latency. The two reflexes working in unison are able to provide stable retinal images through a wide range of frequencies.

Another potential relationship between VOR and OKR is related to VOR adaptation. It has been demonstrated that the VOR response is adaptable in that gain values will be adjusted to accommodate different sensory arrangements. An example is provided by the case of looking through magnified optics such as scuba goggles. VOR will adapt its gain to match the amount of eye movement required to stabilize the image even under the modified conditions. In a study to evaluate the effects of visual scale factor on VOR, Draper (1998) found that visual magnifications of 2x and .5x did result in corresponding VOR adaptations and that the visual adaptation was correlated with simulator sickness. A potential theory exists where OKR provides a tight feedback loop of information to the VOR adaptation process allow it to tune itself to the given conditions. VOR adaptation or speed of VOR adaptation has been hypothesized to be a predictor of simulator sickness potential where individuals who adapt faster are less likely to experience sickness symptoms (Draper, Viire, Furness, and Parker, 1997). If this link is real, it is easy to see how subtle artifacts of poor simulator engineering might delay the VOR adaptation process either through inconsistent feedback or by altering the performance of the OKR through visual anomalies.

6.2 PERCEIVED SELF MOTION

Much of the following description of perception of self motion is taken from LaViola (2000). Under various circumstances, individuals that are static with respect to their environment may experience a compelling illusion of self motion. This effect is known as vection. Vection can occur in naturalistic environments such as looking out the window of a vehicle and feeling motion even due to the movement of an adjacent vehicle event though no self motion is present. These effects have often been seen in virtual environments as well. “Immersive” virtual environments with wide field of view displays or helmet mounted displays where fewer references to a static world exist are prone to causing this effect. In the case of a static simulator, these effects are being generated by changes in the optic flow.

The changes in optic flow provided by the visual system provide both translational and rotational information. In a standard environment, these changes in optic flow would be accompanied by corresponding vestibular information. However, in a virtual environment, the vestibular information is not available for intersensory corroboration. It is the result of this effect that forms the basis for the sensory conflict theory of motion sickness.

The strength of vection can be influenced by several factors. Larger fields of view have been show to produce greater perception of motion. This is likely due to the increased stimulus of peripheral vision which has been shown to have a greater influence on perception of self-motion. Also important is the rate of optic flow where increased flow rates equate to greater perception of speed of vection. Both field of view and optic flow rate are issues that must be dealt with when working with ground based vehicle simulation.

In a typical driving scene there is a high rate of optic flow because the observer's eye point is close to the road surface (low altitude). In addition, there are typically many more features in the scene that are close to the driver such as other vehicles, buildings, signs, roadside vegetation, etc. Wider fields of view are often found in modern driving simulators because there are many instances in driving where full left and right scanning is required to negotiate the environment. Intersections are a good example where you must be able to look 90 degrees left and 90 degrees right in order to check for traffic, pedestrians, etc. before proceeding.

Compared to many virtual environment applications, the potential for vection is higher in vehicle simulators because motion is an inherent characteristic of the application (McCauley and Sharkey, 1992). The potential for vection in driving simulators might even be higher as compared to flight simulators given that flight simulators usually present slower optic flows due to higher altitude eye points (excluding ground operations). In addition, flight operations are rarely executed in close proximity to obstacles, buildings, traffic, etc. Clearly the level of scene complexity and rate of optic flow are typically higher in ground vehicle simulation applications and likely require greater constant attention Therefore, extra precaution must be taken to assure that visual stimuli are presented with as few anomalies as possible.

7 SIMULATOR DESIGN FACTORS INFLUENCING SIMULATOR SICKNESS

There are many issues associated with the design and performance of vehicle simulators that have in impact on how the human operator will react. The next section of this document will define and discuss these issues. While there are some rights and wrongs when it comes to designing a simulator for minimal sickness potential, there are also often many trade-offs that must be made with respect to cost, complexity, and matching the capability of the device to the requirements of the application. Wherever possible, these trade-offs will be discussed with respect to the development of a ground vehicle simulator. The format of the following section loosely follows that of Kolasinski (1995) but will include additional sections, up-to-date references and some discussion of how these issues pertain to ground vehicle simulator design.

7.1 FIELD OF VIEW

Field of view has long been implicated as a contributing factor to simulator sickness (Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley, 1989; Casali, 1986; Kolasinski, 1995; Pausch, et al. 1992). Wide fields of view have the potential to stimulate more of the peripheral visual system which in turn results in greater vection (Kennedy et al., 1988). While vection and

simulator sickness have been reported in narrow field of view simulators, more field of view tends to be an elevating factor (Ijsselsteijn et al., 2001). In fact, vection can be considered a desirable trait in flight and driving simulators where the operator needs to perceive that they are moving through the environment regardless of physical motion. Unfortunately, there is some evidence that vection induces simulator sickness (McCauley and Sharkey, 1992). It seems fairly clear from the literature that as field of view increases, the potential to induce simulator sickness also increases. As always, the simulation designer is faced with a trade-off where the visual system should have just enough field of view to support the requirements of the task being performed (Stanney, et al. 1998).

The availability of HMDs makes us further define how we think about field of view. With traditional display systems where the image is presented all of the time, the field of view is limited by the range of the display media that has been set up. For example, in a 180 degree forward field of view simulator, the effective field of view depends on where the driver is looking. At gaze locations over most of the forward scene the driver will have enough field of view to stimulate the entirety of their central and peripheral visual system (about 120 degrees). However, gazes at or near 90 degrees to the right or left of center the edges of the image display will result in only half of the peripheral visual system being stimulated. With HMDs, the field of view restriction is fixed to the head movement of the operator. That area that can be seen without head movement is called direct field of view. The total area that can be covered with head movement is called peripheral field of view. With HMDs that have direct fields of view of less then 120 degrees, some amount information to the peripheral visual system will be truncated depending on the capabilities of the HMD. However, there will be no limitation to the effective field of view for central vision provided the operator will move their head to reposition their point of gaze.

The field of view required for driving ground vehicles varies somewhat by the tasks being performed. In normal highway driving, the driver needs to be able to scan the environment ahead to determine the physical shape and orientation of the roadway in additional to acquiring self-motion information from the optic flow. At intersections, the driver needs less information about self motion but has an additional requirement to scan left and right looking for potential hazards and checking for traffic. In this case, a minimum 180 degrees forward field of view would be required to safety negotiate an intersection. The requirements of off-road driving are also likely to include an ability to scan a wide field of view as the driver searches for hazards and looks into and around tight, winding roads.

The impact of the constant restriction on peripheral information offered by HMDs on a driving task is not totally clear. Segawa, Ujike, and Saida (2002) evaluated effects of presenting stimuli on the visual field on perceived self speed. They found that perception of speed increased with greater peripheral stimulus area and greater eccentricity of the stimulus. This implies that the sensitivity to perception of self speed may be reduced if restriction is placed on peripheral stimuli. Jamson (2001) did indeed find that widening the field of view on their conventional display driving simulator to 230 degrees from 140 degrees resulted in improved speed keeping and lane selection performance when compared to actual on road driving. It appears that this effect also transfers to lateral lane keeping performance. Kappe, van Erp, and Korteling (1999) investigated the effects of field of view on lane keeping performance while correcting for a side wind. Performance was improved in a wide (150 degrees) field of view configuration as compared to a narrow field of view system. DeVries and Padmos (1997) evaluated the effects of truncated field of view on flying tasks indicate that performance increases as field of view increases up to about 60 degrees where it tends to level out. Other studies indicate that immersion is enhanced by maintaining fields of view 140 degrees or greater (Duh, Lin, Kenyon,

Parker, and Furness, 2002; Duh, Lin, Kenyon, Parker, and Furness, 2001; Prothero and Hoffman, 1995; Lin, Duh, Parker, Abi-Rached, and Furness, 2002).

7.2 DISPLAY FLICKER

Perception of flicker in visual displays has been linked to simulator sickness (Pausch, et al. 1992). The perception of flicker is affected by several factors in a traditional simulator design. Display refresh rate, field of view, and increases in luminance levels all increase our perception of flicker. Therefore, to avoid potentially inducing sickness with display flicker, care must be taken when adjusting these variables. Increases in brightness will result in increased perception of flicker. Increasing the horizontal field of view will also increase perception of flicker. And, of course, the display refresh rate will affect perception of flicker where slower refresh rates will result in greater perception of flicker.

The critical flicker frequency, or the repetition rate above which flicker is not perceived, falls between 40 and 60 repetitions per second. The exact flicker threshold depends on factors that include picture brightness and ambient lighting, but 30 flashes per second is below threshold under any viewing circumstances. Although theatrical motion pictures run at a rate of 24 frames per second, each frame is projected twice, raising the flash rate to 48 frames per second. This is above the critical flicker threshold for relatively low-brightness images in a dark movie theater, but it is well below it for large, bright projected images viewed in lighted rooms.

Speaking more precisely, 48 flashes per second is above the flicker threshold in a dark movie theater for foveal, or straight-ahead viewing, but not for peripheral viewing. This is because peripheral vision is much more sensitive to flicker perception than foveal vision (Boff and Lincoln, 1988). Modern projector display manufacturers are continually driving towards brighter images displays and the potential exists to exacerbate flicker perception with very bright, wide field of view visual systems. Simulator integrators should exercise caution when applying bright displays in wide field of view systems so that flicker perception does not become an issue.

7.3 IMAGE RESOLUTION

Image resolution can have a marked impact on task performance and may also contribute to simulator sickness. A healthy human eye can perceive an image that subtends an angle of about 1 arcmin onto the foveal part of the retina. This angle is affected by the pixel density of the display and the distance from the viewer to the display. One arcmin/pixel resolution roughly equates to about 20/20 vision. Many driving simulators today have effective resolutions of about 3-5 arcmin/pixel (Kemeny, 2000; Jamson, 2001) which equate to 20/60 – 20/100 vision. The FAA requires their aviation training simulators to have effective resolutions of 3 arcmin/pixel or less.

The resulting effects of limited resolution can include drivers missing key features that they should be able to perceive in the environment and potentially causing some amount of eye strain as the eyes attempt to resolve images that cannot be brought into focus. Direct links of low resolution image displays to simulator sickness have not been made. Kolasinski (1995) states that the role of resolution in simulator sickness might be somewhat indirect and can become an issue if it results in increased perception of flicker. In very low resolution conditions, other indirection contributions to simulator sickness might include perception of image blur or slip. Perception of image slip might cause the OKR to attempt to stabilize the image with a

reflexive eye movement or could possibly feed vestibular system poor information resulting in slower VOR adaptation.

In summary, it appears that image resolution has more direct impact on task performance than on simulation sickness. However, attempts should be made to increase resolution to a level that is sufficient for reducing eye strain and making it possible to extract task-relevant information from the scene.

7.4 GRAPHICS UPDATE RATE

The graphics update rate is the rate at which the display is updated based on the most recent interpretation of information concerning the driver's state within the virtual environment. The graphics update rate is typically a function of the capability of the graphics generation hardware/software and the complexity of the visual scene. The relationship is one of inverse proportion where higher levels of complexity typically result in lower sustainable update rates. There are several effects that graphics update rate can have on the potential for simulator sickness. First, decreased update rate can results in increased lag between a given control input and the presentation of the corresponding update of the state of the simulation system. A system running at 30 Hz without prediction algorithms will add a minimum of 32 ms to the total lag of the system without even accounting for the time it takes to poll the control and process the information to provide the viewpoint for the graphics subsystem. Frank, et al. (1988) found that delays in the update of visual information were more disconcerting to simulator drives than were delays in the update of the motion system. A graphic update rate of 10 Hz presenting an out the window view of a vehicle driving 55 mph will only be updated every 8 feet. The resulting presentation appears "jerky" and has the potential to be perceived as flicker (Casali, 1986).

The vestibular ocular reflex (VOR) works internally with its own latency of about 20 ms before an eye movement is made in reaction to a triggering head movement (Draper, 1996). Therefore, the ability of most simulation systems to update the graphics displays is far slower than the nervous system's ability to detect change. The resulting effect is additional cue mismatch which can lead to increased potential for simulator sickness.

In addition to the effects caused by constant update rates, there are additional problems caused when the update rate is variable. It is possible to see variable update rates which reflect the variance in scene complexity that one might encounter in a normal driving simulator such as driving through a complex intersection versus driving on a rural road. If the graphical update rate is allowed to slow down in certain locations and run faster in others, the processes that lead to VOR adaptation can be disrupted. The end effect is that VOR adaptation is slowed or never allowed to fully complete. Recall that slower VOR adaptation has been linked to simulator sickness (Draper, 1996).

7.5 REFRESH RATE

Refresh rate is the rate at which the display system re-draws the graphic view generated by the image generation system. Refresh rate is independent of the vehicle simulation and the rate at which it processes. Each refresh of the visual scene will present the current state of the graphical output from the image generator. So if the image generator were running at 30 Hz and the display system was capable of running at 60 Hz, each of the 30 Hz graphics frames would be drawn twice by the display system. Refresh rate has the potential to impact sickness if the rate is not constant or if it is slow enough where flicker can be detected. Recall from the

earlier section that flicker perception is affected by brightness, refresh rate, and width of the display. Flicker perception is though to be around 30 Hz for a narrow field of view with displays of average brightness. Today's hardware and software are typically able to maintain consistent refresh rates of 60 Hz mono or 48 Hz stereo. At normal illumination levels, the refresh rate should not have an impact on simulator sickness in a modern driving simulator.

7.6 BINOCULAR VIEWING

Simulation displays can be set up to present either monoscopic or stereoscopic visual information. Monoscopic viewing information is essentially viewing the world through one eye or where both eyes see the same picture. Stereoscopic viewing is where each eye views the world from a slightly different perspective due to the distance between them. The human visual system is able to fuse these images together into a single view depending on the point of focus and the disparity between them. As discussed earlier in this document, this effect is called binocular disparity. In addition to binocular disparity, vergence cues are also produced by the stereo display as the observer's eyes move laterally, to position the images appropriately on the retina. Since binocular disparity is one of our strongest cues to depth and shape recognition, it is important to understand the generation processes, what impact they can have on operator performance, and how they may impact incidence of simulator sickness.

The remaining binocular cue to depth that is not accounted for by stereo displays is accommodation. With stereo viewing, the accommodative distance will remain at the screen position, regardless of where the objects are located mathematically. This is a big issue given that vergence and accommodation are highly inter-related as pointed out by Parrish, Holden, and Williams (1992). They note that for a given accommodative distance, there is a limited range of vergence that will result in well fused, in-focus, comfortable view of an object. Therefore, there is a limited amount of lateral disparity that is usable for any display design. There is also some question as to how much disparity should be used to present depth-rich, easy to view images Siegel, Tobinaga, and Akiya, 1998).

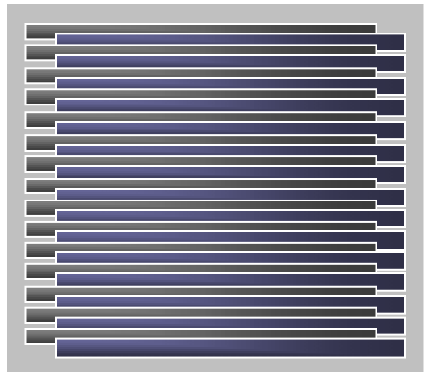
Stereo display systems offer cues to depth by offering two views, one for each eye. There are a number of active and passive techniques for accomplishing stereo presentation. These techniques will be discussed below.

7.7 ACTIVE STEREO

Active stereo is a stereo presentation method that employs alternating right/left eye information on every refresh frame of information and utilizes electronic-shuttering eyewear. When left eye information is presented, the right eye's view is occluded, and subsequently the left eye is occluded when right eye information is presented. This typically requires a minimum refresh rate of 96 Hz (48 Hz update per eye) to reduce the potential for perception of flicker in the scene. The glasses and refresh of the display system must operate synchronously or right/left eye information will drift in and out of proper presentation and the system will become unusable.

"Standard" Page-Flipped (or Quad Buffered Frame-Sequential) active stereo generally requires specific support from the graphics hardware driver, the primitive rendering API such as OpenGL, and the Scene management API such as Performer. Page-Flipped stereo operates at the resolution of the video display, and is the preferred stereo method. When rendering to multiple displays, support for frame synchronization is necessary.

In situations where no driver support for stereo is available, companies such as i-Art Corporation's (www.iart3d.com) Eye3D Premium LCD shutter glasses can be used. Their system provides an external box that connects between the VGA output and the display device. This system provides stereo separation using a technique called sync doubling.

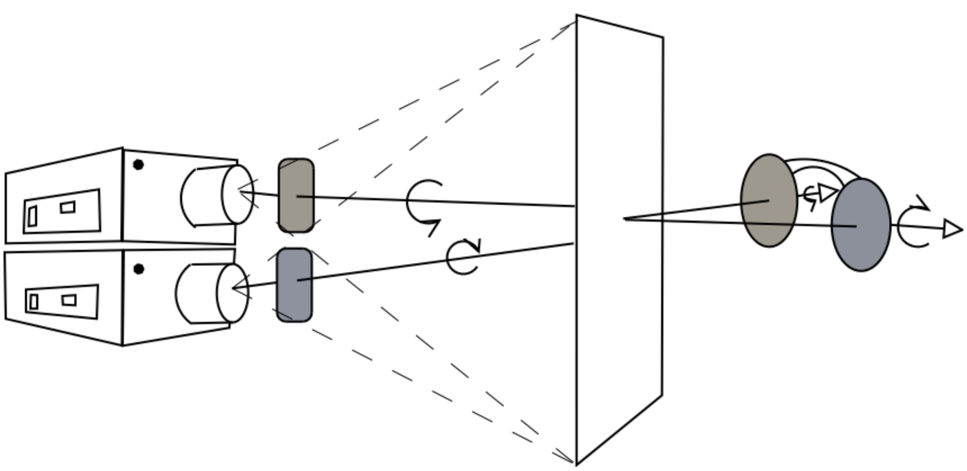


The image on the left is the over/under approach the graphics API must use to render the scene into video memory. The top view is the right-eye image, while the bottom view is the left eye image. The external device inserts a vertical sync signal into the image between the two halves, and the result on the output device is the "interlaced" image on the right. This technique has the obvious disadvantage of halving the vertical resolution. In addition, the application must be able to render the somewhat non-standard over/under viewport image to allow proper separation. It is unclear as to whether this technology, or the Eye3D product, will operate correctly with multiple displays.

7.8 PASSIVE STEREO

An amount of information in this section was taken from resumbrae.com in their discussion of building a low-cost PC based cave.

Passive stereo achieves the separation effect using polarizing filters and polarized glasses, or by encoding the left/right eye images using colorization techniques. Polarized passive stereo requires a dual projector configuration and screens that will not de-polarize the video.



As shown above, lens filters and eye wear are polarized such that each eye can only see the output of an individual projector. The refresh rate of all projectors must be matched, but is not as constrained as the active stereo case, as standard 60 Hz video modes may be used. Projectors should operate synchronously to avoid inter-ocular display distortions. However, depending on the update rate each wall need not be synchronized with adjacent walls.

Linear or Circular polarizers may be used for the filters. Linear polarizers are cheaper, but the stereo effect is lost if the subjects head is tilted. Polarizing glasses are inexpensive, and disposable versions are available. Any CRT, LCD or DLP projection technology may be used as there are no constraints on refresh rate. However, keystone correction or special lenses may be required to assure that the images from both projectors are properly overlaid.

8 ANAGLYPH

Anaglyph (red/blue) stereo is mentioned in passing as a final passive stereo technique. It colorizes left-eye information in red and right eye information in blue. When viewed through red/blue glasses it produces the stereo effect. Color information in the original images in severely distorted, and therefore the technique only works well for black and white images.

9 IMPACT OF BINOCULAR VIEWING ON PERFORMANCE

The impact of binocular viewing on task performance will depend on the requirements of the task itself. There are a number of references that indicate general performance on tasks such as judging distance, object identification, etc. are superior when stereoscopic presentation is used (Ellis and Bucher, 1994; Ellis and Menges, 1995; Merritt, 1991; Barfield, Hendrix, and Bystrom, 1999). While stereo presentation appears to increase presence, (Palmisano 1996; Ijsselsteijn, Ridder, Freeman, Avons, and Bouwhuis, 2001), it's effect on perceived vection is a little less clear. Ijsselsteijn et al. found that stereoscopic displays had no effect on vection where Palmisano found that stereo increased the number of subjects reporting vection and decreased the amount of time for them to report it. Ijsselsteijn et al. (2001) offer an explanation for this. While Palmisano used moving dot stimuli, they used real-world visual scenes which offer many more cues to depth and motion. The implication is that stereo may be less necessary when working with real-world environments that offer texture gradients, interposition, and linear perspective as salient cues to depth.

It is clear also that the configuration of the display system may have an affect on overall task performance. In an analysis of distance estimation capability with a stereo display system, Parrish, et al. (1992) found that subjects tend to over estimate distances to objects behind the screen distance and are fairly accurate at or in front of the screen distance. Given that accommodation and vergence are typically only effective at ranges of less then 16 feet from the viewer, the impact of stereo vision on task performance will be correlated to how much the task relies on information gathered within that range.

DeVries and Padmos (1998) conducted two studies designed to evaluate the effects of various characteristics of HMDs on the operation of unmanned aerial vehicles. In either study, they were unable to detect any performance differences between mono, stereo, and hyperstereo presentation of visual information. Their conclusion was that the task of flying the unmanned aerial vehicle required the pilot to look ahead much further into the scene than what could be enhanced through stereo presentation. In this case, stereo presentation was not able to enhance operator performance due to the type of task at hand.

In an application as dynamic as driving simulation, it is necessary to view and perceive depth at both near and far distances. Judging distances to signs, roadway markings, other traffic, etc. should all benefit from the addition of stereo vision. In an analysis of where drivers look as they negotiate curves on road, Land and Horwood (1995) found that at higher speeds drivers actively split their attention between distant and near (around 1 s) viewing regions. At lower speeds, drivers tend to make use of only the near viewing region. Since drivers are making use of information in the near region, it might be that stereo presentation could enhance their ability to extract information from the roadway scene. In a study to determine the effects of 2D vs. 3D displays for remote off-road driving, Merritt (1991) found that drivers using the 2D displays failed to recognize and avoid hazards such as ditches, burms, rocks, etc. With stereo 3D presentation they were able to detect and avoid the hazards.

It appears from the available literature that stereo presentation can have a positive effect on operator performance provided the task being conducted requires information within the effective stereo display viewing volume.

9.1 IMPACT OF BINOCULAR VIEWING ON SIMULATOR SICKNESS

It is possible to present the eyes with perfect geometric constructions of the visual scene and still end up with negative side effects such as simulator sickness (Siegel, et al. 1998). This is because the brain interprets many cues in cognition when evaluating a visual scene and it is nearly impossible to simulate and present them all correctly. The effect of confusion or mismatch between the cues can result in some incidence of simulator sickness. Stanney, Mourant, and Kennedy (1998) cite Kalawski for identifying binocular rivalry as one of these issues. Binocular rivalry occurs when two images are presented to the observers eyes individually and the dominant eye attempts to dominate the visual system. Disturbing effects and sensations can be experience as a result of binocular rivalry and it is often triggered as competing cues such as changes in luminance, color, and complexity cause dominance to be switched (at least temporarily) from one eye to the other. Negative effects can be strong enough to cause users of desktop 3D display equipment to disable the stereo capability. In fact, Siegel et al. find the negative effects strong enough that they (and others) are in pursuit of a "kindler, gentler" stereo viewing system.

A number of studies have attempted to assess the impact of stereo presentation on simulator sickness. In a direct evaluation of using stereo vs. mono HMD displays Singer, Ehrlich, Cinq-Mars, and Papin (1995) found that while stereo improved subject's short range distance estimation, it also resulted in higher nausea subscale scores on the Simulator Sickness Questionnaire (SSQ). Lowther and Ware (1996) and Palmisano (1996) found that the addition of stereo graphics increased the amount of vection that virtual environment users experienced. Given these limited results it would appear that the addition of binocular visual cues has the potential to increase sickness.

There are a number of factors that can be varied within a stereo presentation that may help lead to a reduction in ocular discomfort. Siegel, et al. (1998) have proposed a stereo concept that will provide good depth information but is much easier to view. Humans can reliably perceive depth from images with interocular disparities that are a few percent of normal viewing. With microstereopsis, a stereo pair is generated with less inter-ocular disparity than then human visual system would normally receive under normal geometric calculation. If a scene contains enough familiar detail, then depth perception can be stimulated by the pair containing less

disparity. With less disparity, there is less physical and mental discomfort as visual perceptual systems attempt to resolve the image. The result is a more comfortable stereo viewing condition.

The addition of binocular visual cues to a driving simulation display may present something of a trade of to the user. On one hand, stereo has been show to enhance near field distance perception and task performance, especially in conditions where the monocular depth cues are degraded. On the other hand, it also appears that stereo can increase feelings of vection and potentially lead to increased incidence of sickness. It seems the most desirable design for a given use of the simulator will depend on the requirements of the task. Off-road driving where target detection and terrain interpretation are very important may benefit from the addition of stereo presentation. On-road driving may not benefit to the same extent because drivers get much of their information from evaluating the far visual scene rather than close around them. Of course, there are tasks in on-road driving that might benefit from enhanced near-field depth perception but perhaps they are not common enough to warrant the use of stereo.

9.2 HEAD MOUNTED DISPLAYS

Head mounted displays (HMD) offer a number of potential advantages to driving simulation applications. First, there is a freedom from visual field of view restrictions experienced when implementing traditional fixed display technologies. Wider fields of regard are required to perform appropriate visual search and monitoring tasks while driving. With appropriate head tracking technologies, the effective field of regard could be as much as 360 degrees. Second, there is much less infrastructure required to support an HMD-based system due to the elimination of the physical display medium. In addition, the reduced overall footprint of HMD-based simulation systems make them more portable, increasing their applicability to a wide variety of driving applications. Lastly, the cost and complexity of HMD-based systems might also be lower due to elimination of physical display infrastructure and also a reduction in the required graphics generation requirements. Where in some traditional simulator implementations several graphics generators or channels are required to create a wide field of view visual scene, the HMD-based system would only require a single graphics generator. Even though there are a number of compelling potential benefits to applying HMD display technologies in driving simulation, there are also some potential drawbacks. The drawbacks and limitations of the technology will be discussed in the following paragraphs.

While current HMD technologies provide unlimited field of regard, there are serious restrictions on instantaneous field of view. Most systems offer fields of view that are 50 to 25 degrees horizontal field of view which can be expanded by modifying the amount of ocular overlap. Human eyes have an approximate 120 degree horizontal overlap between their fields of view. An ideal head mounted display system will allow both eyes to clearly see what the other can see within this overlapping region. Most HMDs have two independent channels, one for each eye, and some designs do not fully support this overlapping region in a way that makes sense to the brain. Therefore, it is important to understand the viewing requirements of the simulation and the locations of objects that will need to be observed. Without 100% overlap, objects close to the viewer may cause disorientation as the eyes cannot see the images as the brain expects them to be seen. For instance, partial overlap can lead to visual illusions such as the appearance of a curved moon at the monocular border where binocular rivalry is greatest. The most appropriate modification of ocular overlap for a general driving simulation application has yet to be determined but will likely be something less than 100%.

To understand the impacts of reducing field of view from our unmodified capability, we must refer back to the basic functions of the anatomy of the eye. Recall from the earlier section on central vs. peripheral vision that central vision is good for static viewing and identifying what something is. Peripheral vision is good for motion sensation, spatial orientation, and supporting gaze stability (Leibowitz, 1986). With respect to driving, Leibowitz identifies that experienced drivers tend to use peripheral vision for steering the vehicle while using central vision for identifying potential hazards in the world. If instantaneous field of view is limited with the HMD, there may be an effect on the driver's ability to effectively steer the vehicle. For instance, Wood and Troutbeck (1994) found that with narrow fields of view it is more difficult to drive a vehicle in a straight line down a straight road. In several recent studies, controlled evaluations of driver's ability to control a vehicle have indicated some performance differences.

In an evaluation of several display types with pilots performing a flying task, de Vries and Padmos (1998) found that operator performance was worse with the HMD than with head slaved or full screen displays. However, they attributed the performance reduction to the considerable image delay (190 ms) and heavy weight of their system as opposed to field of view reduction. They came to this conclusion because a limited field of view head slaved option did not result in a corresponding reduction in performance. They go on to recommend adding vehicle references when using HMDs to help provide a stable reference from which adjustments of orientation can be made. Kappe and Padmos (2001) performed a similar study to evaluate the effects of wide screen, head slaved, and HMD displays on ground vehicle driving performance. They found similar results where the HMD resulted in a negative effect on driving performance.

In an assessment of a fixed base driving simulator that makes use of an HMD, Mourant and Thattacherry (2000) found that subjects reported more oculomotor discomfort symptoms on an SSQ than what has typically been found in driving simulation studies using the SSQ. They attribute the shift from more nauseogenic symptoms to oculo-motor symptoms to advances in virtual environment technology.

Burns and Saluaar (1999) conducted an evaluation of driver behavior using an HMD in a driving simulator as they negotiated their way through intersections and ensuing turns. They found that drivers with the HMD made longer glances but also made the same number of glances as did drivers in a real vehicle. They also found differences in drivers speed after turns, lane keeping ability, and subjective workload where use of the HMD decreased performance and increased workload. In a more theoretical study evaluating perception of self rotation with an HMD, a wide screen, and a wide screen with field of view limiting blinders, Schulte-Pelkum, Riecke, and Von der Heyde (2003) found that in general subjects tended to underestimate the amount of rotation they had experienced but more so with the HMD display. They concluded that the effect had to do with something other than field of view given the significant difference between performance in the HMD versus the wide screen with limited field of view blinders. In a second study, Schulte-Pelkum, Riecke, Von der Heyde, and Bulthoff (in press) evaluated the effects of curved versus flat screens in perception of ego-rotation through visual stimuli. They found that subjects underestimated rotation with curved screens but overestimated rotation with flat screens presenting the same field of view. They attribute the differences to subjects perceiving rotation as translational movement with the flat screen displays.

Ruspa, Scheuchenpflug, and Quattrocolo, (2002) evaluated two simulator designs that were to be used for ergonomic vehicle evaluation. The first configuration was a 100 degree horizontal field of view fixed display system and the second used an HMD with 40 degree horizontal field of view. Data collected with these systems was compared with some data collected in actual

vehicles. The key finding was that the subjects did not necessarily make use of the additional field of regard that was afforded by the HMD. In a backing task in the real vehicle 28 of 36 subjects turned around to look while backing. In the HMD condition, only 1 of the 36 subjects turned around to look while backing. Others have reported a reduction in head movements while using an HMD (deVries and Padmos, 1998; Burns and Saluaar, 1999). Wells and Venturino (1990) conducted a study of subjects performance on a target detection task with wide and narrow field of view HMDs. With the wider field of view, subjects moved their heads less but at faster rates when they did. The reduction in normal head movement might be caused by several factors. The weight and inertial of the hardware itself might be enough to cause some to not move their heads often. If display lags or tracking errors exist, some may not move their heads to avoid the “penalty” of experiencing the feelings of discomfort that these effects can bring. If HMDs do result in a reduction in voluntary head movement, it would likely result in reduced performance on driving tasks especially in environments where a lot of lateral scanning is required.

There appears to be a trend in the literature to date that would indicate driving performance will be worse with an HMD. Several studies have evaluated theoretical HMDs where a wide screen simulator system is used but a field of view restriction is placed on the driver through special glasses or masks (Van Erp and Kappe, 1977; Pepper, 1986; Spain, 1988). These represent “perfect” HMDs in that there is no latency or head tracking error and the weight of the head mounted hardware is minimal. These studies have failed to find any differences between their “perfect” HMDs and wide screen simulation display. Therefore, this has caused some to hypothesize that it is not the field of view restriction that negatively impacts performance but rather it is the visuo-motor interference caused by tracking latency and error that is the culprit. The real question is whether technical advances such as faster processors, more accurate tracking, and better prediction algorithms can solve or partially eliminate performance disparity. Given the potential benefits of being able to use HMD technologies including reduced overall costs, smaller footprint, etc. the issue certainly deserves more investigation and research.

The HMD might also have an impact on potential for simulator sickness. The nature of this impact is as yet unknown. It has been shown that an increase in simulator field of view and the resulting increases in peripheral stimulation cause increases in simulator sickness (Kolasinski, 1995). Therefore, it is possible that the field of view limitations caused by HMDs might actually reduce simulator sickness (Pausch, et al. 1992). Of course there are a number of other less optimistic factors that need to be considered as well. Most lighter weight HMDs make use of LCD technologies. Image smear caused by phosphor decay in rapidly moving images from LCD displays has been theorized to be a contributing factor to simulator sickness.

HMDs require head tracking in order to present the appropriate orientation of view. Latency and error in the data being fed to the visuals system can also be a cause of simulator sickness. Latency affects the visuo-motor system in that it triggers a change in the vestibular ocular reflex response in order to accurately stabilize the image on the retina. The adaptation does occur naturally but will take some period of time to accomplish – anywhere from 5 minutes to hours depending on how much adaptation is required and how consistent the change. Variance and error in latency response can cause a prolonged adaptation period (Draper, 1996). This finding indicates that if you are going to be “off” with the tracking values, it is better to be consistently off so the visuo-motor system can adapt to the error. The longer the subject experiences the sensory stimulus without adaptation, the greater the potential for sickness. To forgo the adaptation process, it would be necessary to reduce latencies in the head tracking processes down to around 10 ms or so (Kemeny, 2000).

Several HMD hardware design factors can have an impact on potential simulator sickness. The weight and inertia of HMDs has also been implicated as a potential cause of simulator sickness. HMD weight can affect the body's interpretation of the mass of the head and subsequent movements will distort the signaling produced by the otoliths responsible for perceiving tilt (DiZio and Lackner, 1992). This will in turn create a conflict between the proprioceptive and vestibular systems. Controlling for all other factors, they found that the weight of the head mounted gear alone is enough to trigger sickness symptoms without consideration of any visual stimuli. HMDs with a weight as light as 600 g. have been shown to cause sickness.

Inter-pupillary distance (IPD) is a design parameter or an adjustment setting associated with HMDs. The idea is that you adjust the width of the lensing or displays in the HMD to more closely match the individuals natural IPD. With respect to the effects of IPD supported by the HMD, Kolasinski (1995) summarized a study by Regan and Price. They hypothesized that individuals with departures from the design IPD would suffer eye strain, headaches, and visual system problems. They found instead that for the most part, only those with IPDs greater than the design IPD suffered ocular problems. The majority of persons in their study had IPDs smaller than the design IPD. In those cases, it appears that the eyes are able to converge using normal binocular visual response without discomfort. However, those that would have been required to diverge their eyes would experience greater discomfort because this is not typically the way eyes need to move to resolve an image. Therefore, on systems where the IPD is not adjustable to the individual, it is necessary to make sure the design IPD is less than the subject population's IPDs. The best approach might be to adjust for each individual and slightly bias towards setting it too narrow.

HMDs offer exciting advantages as display solutions for driving simulators. However, as shown in the discussion above, there are a number of open research questions that must be answered before we can be sure they are a viable and optimal solution.

9.3 MOTION CUEING

Motion systems have been added to many modern driving simulators in hopes of increasing realism, validity of operator responses and reducing simulator sickness. In addition, many researchers have hypothesized and hoped that the addition of accurate motion cues might reduce overall levels of simulator sickness experienced by simulator drivers. The results of reported implementations and studies executed to date indicate some successes but overall there still much to be learned about this topic.

A good many flight simulators have been equipped with motion base systems because they have been thought to reduce sickness, enhance training effectiveness, or were simply desired by the user community (McCauley and Sharkey, 1993; Casali, 1986). In a review of flight simulator sickness incidence reports, Casali (1986) noted at least seven separate flight simulator devices with motion cueing systems that had significant proportions of users experiencing at least moderate levels of simulator sickness symptoms. One simulator in particular was able to significantly reduce their reported levels of sickness by adding motion cues Sinacori (1967). Most of these reports were from simulators that were developed in a technical era vastly different today where some of the sickness incidence might have been caused by other confounding factors such as poor visuals presentation, large transport delays, etc. To better understand the contribution of motion cueing to simulation systems we will concentrate on modern reports that performed controlled studies to evaluate the effects of motion and no-motion operational conditions.

Probably one of the better known evaluations of motion versus no-motion is Sharkey and McCauley (1992). In this study, the researchers compared results from pilots flying specific maneuvers in NASA's Vertical Motion Simulator (VMS) to results collected in a fixed base simulator. The VMS was equipped with the most capable motion base available at the time. The reported results indicate that that motion cueing provided by the VMS did not eliminate or reduce simulator sickness symptoms for the maneuvers flown. Similar results were found by Watson (1995) in a high fidelity, motion-base driving simulator although power analyses indicated there might have been an effect if more subjects had been run.

Even with the most capable motion base available, it is impossible to duplicate the large accelerations felt in an aircraft or ground vehicle. Other strategies must be used such as scaled cueing and washout algorithms. Scaled cueing is simply a technique where a scaling value is applied to the forces being applied to the driver in the simulator. So at a scaling factor of 0.25 and a real world deceleration of .4 g, the driver of the simulator would experience a .1 g deceleration. Scaling allows for representative acceleration inputs without extending beyond the limits of the motion hardware.

Washout algorithms provide two functions. First, they reposition the operator using tilt to make use of part of the gravity vector to provide sustained acceleration in the lateral or longitudinal direction. Second, they work to reposition the motion base in the center of its operating envelope after acceleration has been applied. The repositioning movements must be conducted below the threshold of detection of the operator in order to avoid providing inaccurate cues. The threshold of human roll detection is about 5 deg/s (Ares, Brazalez and Busturia, 2001). If realigning rates are less than this threshold, realignment of the gravity vector in the local frame is not detected by the vestibular system. To solidify the illusion of sustained acceleration, the visuals system must present the driver's view with the motion base orientation subtracted. For example, to provide a sustained lateral acceleration to the left, the motion base would tilt to the right and the visuals would also tilt to the right. So the driver is feeling a lateral acceleration provided by gravity due to tilt and the visuals have also tilted to the right to visually indicate that the driver is not tilting at all. This effect is called the visuo-vestibular illusion. Depending on the capabilities of the motion system and the effectiveness of the algorithm, there can be instances where unwanted or inaccurate cues are presented. The impact these cues have on VOR adaptation and cue conflict on simulator sickness are not known but presumed to be negative.

When motion is used in driving simulation, the impact on performance depends somewhat on the maneuvers being performed. Advani and Hosman (2001) state that driving skill-based behaviors are affected by motion cues much more than knowledge-based behaviors. Therefore, motion cues will have greater impact on vehicle disturbance and recovery maneuvers than on lane tracking tasks. The driver relies on the quality of the motion cues and close-coordination of corroborating visuals information to make appropriate responses. They go on to state that motion systems can be pre-adjusted and purpose-built to provide the best response for a given set of driving response requirements. The adjustments might include modification of the geometry of the database or pre-positioning the vehicle at an advantageous position in the movement envelope prior to a maneuver. Indeed, Nordmark, Palmkvist, and Sehammer (2001) have developed their simulator to be able supply large amplitude (0.8 g) acceleration in one direction. They have built the system so they can rotate the simulator to either provide the large acceleration in the lateral or longitudinal direction depending on the needs of the scenario to be driven.

There are a number of studies where positive results have been found from adding motion cueing. Curry, Artz, Cathey, Grant, and Greenburg (2002) conducted a study to compare their fixed based simulator to their 6 DOF motion base simulation. Their fixed base simulator is a 140 degree horizontal field of view system and the motion base system 180 degrees plus 125 degrees to the rear in a dome on a 6 DOF motion base. After conducting similar driving tasks for an equal amount of time, they reported lower SSQ scores for those subjects that drove the 6 DOF motion base simulator.

Reymond, Kemeny, Droulez, and Berthoz (1999) conducted as study on the Renault driving simulator to asses the impact of motion on driver behavior as they negotiated a virtual test track. The Renault Driving simulator has a very capable 6 DOF motion platform and 150 degree forward field of view. Each subject drove the simulator with and without motion cues. The addition of motion cueing caused drivers to slow down closer to the optimal speed as compared to the no-motion condition. The authors hypothesize that the lateral acceleration cues which are linked to increased perception of risk (Ritchie, McCoy, and Welde, 1968) caused drivers to slow their speed to more normal levels as they chose to mitigate their risk of running off the track. This result suggests that drivers really do make use of acceleration cues as they evaluate risk as opposed to a primarily visual assessment of conditions. In this study, the addition of motion modified driver behavior to be closer to responses found in the real world.

Siegler, Reymond, Kemeny, and Bertholz (2001) conducted another study on the Renault Dynamic Driving Simulator to evaluate the effects of motion on some elementary driving tasks; braking and cornering at intersections. This particular simulator has limited amplitude motion capability. Typically in fixed base simulators, drivers will exhibit unrealistic braking behavior where grossly over exaggerated inputs are made. They found that when the motion was turned on, drivers made brake inputs that were closer to what could be expected in the real world as opposed to the abnormally large inputs that were made when driving in the no-motion condition. Another interesting finding was that drivers in the no-motion condition adapted their behavior across the 4 trials by gradually making smaller and smaller inputs as they learned how the system would respond. In the motion condition, the responses remained consistent from trial to trial. Siegler, et al. also found differences in cornering behavior where drivers made wider turns when the lateral acceleration cues were present. They conclude that it is difficult to make interpretations about the cornering behavior because you must take driver cornering strategy into account when determining the optimal path.

Several authors (Sharkey and McCauley, 1992; Barrett and Thornton, 1968) indicate that perhaps less expensive, higher frequency vibration transducers mounted on the occupant seat might help mask some of the proprioceptive and vestibular cues that might conflict with visually implied motion. In addition, real world driving applications typically do include some amount of higher frequency vibration which may be an important cue to the perception of vehicle velocity.

There does appear to be benefit from tuning motion systems to the types of maneuvers the driving simulator is expected to support. Grant, Artz, Blommer, Cathey, and Greenburg (2002) performed a tuning process on their 6 DOF motion base simulator to optimize for a lane change event. They compared subjective responses of realism for 10 different motion tuning parameter sets and found that there are significant differences between parameter sets. This would indicate that tuning the motion base to a specific set of operational parameters is a required process when trying to optimize driving simulator fidelity. Kuge, Kubota, and Itoh (2002) performed evaluations of motion tuning parameters on the Nissan Driving Simulator which is a large 6 DOF motion system with visuals off motion.   They conclude that adaptive parameters

sets should be created to adjust motion scaling to the needs of the drive or even to the needs of the individual event.

Some researchers have found that when it comes to combining motion and visuals presentation, less motion might be better. Barnes (1987) reported on a flight simulator developed with a motion based mounted inside a fixed dome. The best results were achieved when a 3 DOF configuration was used to present pitch, heading and roll plus a little translational movement to represent buffeting. Their attempts to include a motion algorithm with tilt coordination to provide sustained acceleration did not provide the results they were looking for. They concluded that in a visuals off motion simulator, the pilot gets conflicting cues from the visual presentation and some stationary reference marks in the display system. The edges of the display, seams between screens, raster lines in the display, and the floor of the dome all provided salient cues as to what was earth stationary. These references defeated the visuals correction for tilt algorithm inputs and provided a earth stationary spatial awareness that conflicted with the simulation's spatial orientation. After eliminating the tilt portion of the motion algorithm, thus eliminating sustained accelerations, they found that pilot performance and subjective assessments were much better than with the more complex model.

Romano (2001) conducted a study designed to evaluate different types of motion that could be supported through the small motion base in a CAVE-based driving simulator. The design of the study provided for paired comparisons of motion conditions presented in an order of increasing cue fidelity potential. Subjects drove the simulator through an off-road driving scene and then provided their subjective response as to which motion condition felt more realistic. The order of motion conditions is presented below:

- No motion
- Roll and pitch only
- Roll, pitch, and heave
- 5 DOF with tilt coordination with motion base orientation subtracted from visuals
- 5 DOF with tilt coordination with motion base orientation not subtracted from visuals

The results of these comparisons are shown in Table 2 below:

Table 2: Motion Cue Preferences

Option One	Preference		Option Two
No Motion	0	6	Roll and Pitch Only
Roll and Pitch Only	1	5	Roll, Pitch and Heave
Roll, Pitch and Heave	4	2	5 DOF with Tilt Coordination
5 DOF with Tilt Coordination	2	4	5 DOF with Tilt Coordination with motion base orientation cues in visuals

The most important finding in that study was that all drivers preferred some type of motion cueing over the no motion condition. Exactly what type of motion was best is a little less clear. In the CAVE-based driving simulator, subjects preferred 3 DOF motion with roll, pitch, and heave better than either the no motion or roll and pitch only motion conditions. This is not surprising as it is expected that more degrees of freedom in the motion algorithm should provide a more realistic response. The surprising result was that when comparing the 5 DOF with tilt coordination conditions, subjects preferred the condition where the motion base orientation was not subtracted from the visuals presentation. From an engineering standpoint, the subject's preferred condition is incorrect. To make use of the visuo-vestibular illusion of sustained

acceleration, the motion base position must be subtracted (Dagdelen, Reymond, and Kemeny, 2002).

There are several potential reasons why the subjects might have preferred the condition that did not subject the motion base position from visuals. First, the nature of the display system is such that it provides salient cues to angular orientation and what is earth-stationary. This provides conflicting information about what is the most appropriate rest frame for the vestibular system to work from resulting in false spatial perception (Barnes, 1987; Prothero, 1998; Prothero, Draper, Furness, Parker, and Wells, 1997). Another explanation might be that additional requirements for moving the visual scene exacerbated visual lag or scene movement artifacts. The visual scene will need to be repositioned more when motion orientation is being subtracted from the visuals display. Any artifacts that are present due to scene repositioning such as visuals lag and blur would be made worse in that condition and could potentially induce simulator sickness symptoms.

The results of surveying the literature with respect to motion cueing might be summarized as follows. There are numerous examples of improving driver performance through the addition of motion cues. However, adding motion cueing does not guarantee that simulator sickness will be reduced. There are examples where the addition of motion has contributed to sickness reduction but there are also many examples where it has not. There are many confounding factors that determine the success or failure with respect to reducing sickness, including the correlation with the visual presentation, tuning of the motion drive algorithms, transport delays, and elements of the driving task. It is believed that there is great potential for tightly coupled, accurate motion to reduce simulator sickness.

9.4 CALIBRATION

Appropriate maintenance and calibration of a simulation system is critical to reducing simulator sickness potential. McCauley and Sharkey (1992) point out that while good engineering may not be a solution to simulator sickness, poor engineering will certainly contribute to the problem. They go on to point out that there are a number of factors that need special attention. The visual system should be calibrated and aligned to reduce any visual artifacts that may be presented such as blurred images or images that overlap. Care should be taken to position the viewer in the appropriate location such that the image presented from the eye point in the simulator matches the eye point of the actual operator. Subtle errors can have confounding effect and can cause the presentation of unwanted cueing.

9.5 TRANSPORT DELAY

Transport delay refers to the amount of time it takes to detect an operator input, process the new state of the simulator based on the input, and return to the operator the resulting changes in the state of the simulation. The resulting effect of transport delay is believed to cause additional sensory conflict between the visual and vestibular systems that might lead to simulator sickness and performance decrement (Draper, 1996; Frank, Casali, and Wierwille, 1988; Pausch, et al. 1992). In addition, in driving simulators, delays can also cause operators to perform self-induced steering oscillations that can exacerbate the problem through increases in visual artifacts caused by yaw rotation in the display. These delays are inherent to an iterative computation system and may be contributed to by a number of difference sources including time to retrieve information from sensors, time to compute resulting changes in simulation state, and time to enact the resulting output such as visuals display change or motion base reposition.

A review of studies looking at the effects of transport delay in flight simulators is included in Pausch, et al. 1992). They cite Westra and Lintern (1985) in their work to evaluate delays on a helicopter landing simulator. They found that pilots were aware of performance difficulties in the longer lag condition (217 ms versus 117 ms) which was backed up by objective data. Uliano, Lambert, Kennedy, and Sheppard (1986) were also reported. They manipulated system lags in a flight simulator to be 215 ms, 177 ms, and 126 ms. They found that pilot performance was worse in the longer lag condition and there were no differences in illness between lag conditions. Westra et al. (1987) were reported to have conducted a second study using lags of 183 ms and 117 ms. They found that the smaller lag condition resulted in small performance improvement.

While there has been some decent research conducted on transport delay in flight simulators, there is some question about how well the results transfer to driving simulation. It is possible that driving simulators require a closer coupling between the driver, vehicle state, and operational environment than flight simulators. In a study designed to assess effects of transport delay for visuals compensation on driver perception, Dagdelen, et al. (2002) found that longer delays resulted in driver perception of incoherence between their commands and the resulting experience. Some of the participants reported feels of skidding or moving up and down as the perceptual result of this incoherence. A secondary finding was that in a fixed base simulator the effect was reported by subjects at around 100 ms whereas in the motion base simulator the effect was not reported until delays reached 700 ms. The result for the motion base simulator seems rather large given the abilities of the human perceptual systems and the results gathered from other flight and other driving simulators. The authors do not provide an explanation for this apparent insensitivity to transport delay for that particular system.

Cunningham, Chatziastros, von der Heyde, and Bultoff (2001) manipulated transport delays on a high fidelity driving simulator. They evaluated steering performance as drivers negotiated a curved route at fairly high speeds. Their focus was to determine how drivers adapt to the delays and if the adaptation transfers to other driving conditions. The delay values they used were 130, 230, and 430 ms. In their first experiment they found that drivers did learn to adapt to the delays but the longer the delay, the longer the adaptation period. In addition, they found that a subsequent removal of the delay resulted in a renewed decrement in performance. In their second experiment, they determined that the adaptation or learning accomplished in the first experiment generalized to a variety of different road types. So, while subjects can adapt and learn to drive with significant transport delay, their speed of learning and subsequent unlearning will depend on the magnitude of the delay. The longer the delay, the longer time perios required to adapt. A threshold of how small transport delay must be to maintain real world (non-adapted) driving performance is not yet known. At least one author (Kemeny, 2000b; Kemeny, 2000a citing Bloche, Kemeny, and Reymond, 1997) indicates that the value must be less than 50 ms. With little prior research to go on, the effect of transport delay on driving simulator drivers is not well understood (Kemeny, 2001).

There is some evidence that there are influences on driver performance and on incidence of sickness and that the effects may be independent. Current literature indicates that increases in transport delay lead to decreases in driving performance but not necessarily increases in simulator sickness. In driving simulation, delays are of primary interest in the visuals and motion systems. Frank, el al. (1988) performed a driving simulator study to determine the impact of both motion and visual delay and found that visual delay was more disconcerting than motion delay. They concluded that both visuals and motion delay should be minimized but it was more important to minimize that of visuals if trade-offs need to be made between the two.

It appears from the literature that most efforts to minimize effects of transport delay on motion-based simulators have concentrated on reducing delays of the visuals systems and the motion systems independently to the greatest extent possible. In terms of how transport delays correspond to cue conflict theory, it might be that rather than thinking of motion and visuals delays as independent factors where the designer works to reduce both, it might be that coordination of the two is most important (Casali, 1986).

An additional form of transport delay must be considered when using head tracked displays such as an HMD or stereo CAVE. Recall from earlier discussion that in order to provide the correct stereo offset views to each eye, the graphics system needs to know the orientation of the driver's gaze prior to generating the scene(s). Head tracking systems come in a variety of forms including optical, magnetic, inertial, and ultrasonic. They make use of sensors and software to provide values for head orientation. The process of interpreting the sensors, computing head position, and transmitting the data back to the visuals system takes an amount of time that adds to transport delay.

The effects of lag in head tracking will likely vary between HMD and CAVE stereo displays due to differences in the impact of lag on the presented image (Kijima, Yamada, and Ojika, 2001). In an HMD, lag is applied to the entire view that is being presented and will be affected equally in the vertical and horizontal directions. Any movement of the head requires a substantial reposition of the entire image, regardless of the dimension of movement. In this case, the lag applies to the entire view. With CAVE stereo displays, the effect of head movement on the image to be displayed is primarily the separation of objects that will account for binocular disparity. The majority of the image remains stable with head movement while there will likely be some lag effect on the binocular separation between objects. Because object separation is a function of the distance between the viewer's eyes which lie in the horizontal plane, horizontal movement results in changes in the image while vertical movement results in hardly any change of the image. Thus, the lag is only a factor during horizontal head movement and does not affect the full view image.

Lags in the reposition of a full screen image, as seen with HMDs, have a higher potential to cause simulator sickness because the visuo-vestibular system has a more difficult time stabilizing the retinal image when even small lags are present. Movement in the scene detected by visual systems after the vestibular and proprioceptive systems indicate the head is stable likely result in detection of image slip. Detection of image slip can affect compensatory functions such as opto-kinetic reflex, vestibular-ocular reflex, and ocular accommodation. These sensory systems function quickly and can detect changes in less than 20 ms (Draper, 1996). Therefore, just about any lag attainable with today's technology will result in some amount visuo-vestibular cue disturbance and likely incidence of simulator sickness. Hettinger and Riccio (1992) conclude that motion sickness occurs most frequently when there is perceivable lag between head movement and regeneration of the visual scene. Problems such as these have been one of the serious drawbacks that have limited HMD use in wide scale applications.

Efforts have been made to reduce the amount of transport delay associated with tracking devices through the use of predictive delay compensation algorithms. The algorithms make predictions of orientation based on the current and previous states of the system. The resulting predicted orientation is then transmitted to the visual system to be used to provide the most reasonable view. Algorithms have been applied to motion base position and also to head trackers for head orientation and position. The benefit of using a predictive algorithm is that effective delays in head tracking position can be reduced from a typical 100 – 150 ms down to

around 20 – 30 ms. The drawback of using the algorithm is that they do introduce some amount of error and the error is variable. Depending on the parameters of the predictive equations, errors include phase lag and overshoot.

9.6 ENVIRONMENTAL CONDITIONS

Temperature has long been thought to contribute to simulator sickness. Several physiological changes occur as a result of simulator sickness. Heart rate, blood pressure, respirations, and skin temperature all increase as a result of experiencing virtual environments. The relationship that ambient room temperature has with these physiological changes is as of yet unknown but is thought to elevate the magnitude and rate of awareness of simulator sickness symptoms. As a precautionary process it is recommended that adequate ventilation and temperature control be built into any virtual environment laboratory.

9.7 SIMULATOR ADAPTATION

The human nervous system is a very complex set of mechanisms and process but is also highly adaptable. This is evident from examples of microprocesses discussed earlier such as the adaptation of the vestibulo-ocular reflex and opto-kinetic responses with variations of input stimuli. At the same time, it is also generally accepted (Kennedy, Stanney, and Dunlap, 2000) that simulator sickness increases with time within a session and decreases over successive sessions. This effect has been confirmed to apply to driving simulation and may vary as a function of scenario intensity and consistency of the cue presentation factors (Watson, 1997). In a study to quantify adaptation as a function of scenario intensity and motion cueing, Watson found that SSQ total sickness, disorientation and ocular discomfort scores dropped by as much as 2/3 from the first to the third exposure. However, nausea subscale scores only showed decline after the 6th exposure resulting in a recommendation of 5 or more sessions to allow subjects to become adapted. Watson also recommends limiting scenario intensity during first few exposures to help facilitate adaptation. McCauley and Sharkey (1992) make similar recommendations including keeping exposure durations short and limiting aggressive maneuvers.

The issue of adaptation raises some interesting questions with regards to exposure and validity of application results. Applications of driving simulation such as research, training, design validation, etc. are typically challenged when it comes to available simulation resources. Cost and logistical constraints often result in users trying to get the most from the simulation in the shortest period of time. This conflicts to some degree with the recommended practices of allowing simulator drivers multiple, relatively benign sessions to adapt before getting to the heart of the simulation application. Without understanding the effects of simulation exposure on driver performance and motivation, it is difficult to generalize research results in the simulator to real driving. Early driver training scenarios have the potential to result in less transfer of training simply because drivers are learning to drive the simulator as opposed to focusing on the lessons that the scenarios hold. Regardless of the application, the users of simulation should strive to understand the effects of exposure and adaptation on their expected results.

9.8 VISUAL VEHICLE REFERENCES

Driving simulation systems come with a variety of cab and control configurations. The most elaborate make use of real vehicle hardware that is modified with appropriate electronic and

mechanical instrumentation to allow communication with the simulator for detection of input and provision of resulting feedback. The obvious advantage of these systems is that they provide a highly realistic and familiar environment for simulator drivers. Elements that are important include accurate orientation and feel of controls, feeling of “presence” in a vehicle, and appropriate visual presentation. Key elements of the visual presentation include the ability to view vehicle references such as the vehicle hood, roof, A-pillars, and mirrors.

Other less elaborate simulators make use of partial vehicle cabs, real vehicle controls only, game controls, or joysticks. With some of these options, the visual vehicle references such as the hood, roof and A-pillars will not be present. In these cases the simulator designer has the option of drawing a virtual vehicle cab in the scene or not presenting the references at all. There is some data that suggest drivers make use of visual vehicle references as a comparator indicating vehicle orientation with respect to the road. The visual references make it easier to determine when the vehicle is pointed where the driver wants it to go. Several researchers have looked into the performance and preference effects of presenting visual vehicle references.

DeVries and Padmos (1998) conducted a study to evaluate competing display methods for unmanned aerial vehicles, a task that is very similar to vehicle simulation. They found that pilots performed more accurate vertical route following and rated the task to be less difficult when references were present. They conclude that vehicle references generally improve task performance and simplify the control tasks significantly.

Kappe, Korteling, and van Erp (1999) performed an evaluation of display types while operating a driving simulator. They compared narrow FOV, wide FOV and head-slaved display options. For each, they tested lane keeping performance with and without the presentation of virtual vehicle references. They found the addition of vehicle references improved lane keeping ability dramatically in the narrow FOV system but less so in the wide FOV and head-slaved display conditions.

In a subsequent study, Kappe and Padmos (2001) evaluate seven different display concepts for use in driving simulators. The display types included full screen (160 degree FOV), full screen with head mounted mask to limit FOV, head-slaved window discreet, head-slaved window continuous, HMD with see-through vehicle references, HMD without vehicle references, and HMD with virtual vehicle references. All conditions were presented with the driver in a real vehicle cab so that real vehicle references could be seen in all conditions except for the HMD without vehicle references and the HMD with virtual vehicle references. In general they found that driving with the HMD reduced performance but not nearly as much when vehicle references were present. They recommend that if an HMD is used that vehicle references should be generated in the scene.

9.9 INDEPENDENT VISUAL BACKGROUND

Recent research by Prothero, Hoffman, Furness, Parker, and Wells (1995) has put forth a new hypothesis which addresses how the sensory systems perform position, motion, and orientation judgements. The “rest frame hypothesis” arises from the notion that human sensory systems derive their judgements about self motion from selected frames of reference. There is a strong tendency to select references frames that are perceived as being at rest. Therefore, the hypothesis is that there are multiple frames of reference presented to an observer all the time. The nervous system chooses one of the reference frames to perceive as stationary and then all

judgements of motion are derived from it. This frame has been called the selected rest frame (SRF) (Prothero, 1998). Under some circumstances, confusion about which frame of reference is actually stationary prohibits the brain from make a determination of SRF. As applied to virtual environments, immersion is driven by the extent to which the virtual presentation can become the SRF (Prothero, et al., 1995).

Selection of the SRF is heavily influenced by visual information because visual presentation usually provides the largest and most salient set of cues from which a determination of rest frame can be made (Prothero, 1998). This correlates well with the generally accepted notion that mismatches and re-arrangements of visual stimuli are more powerful than other cues in their potential to generate simulator sickness symptoms. The influence of rest frame selection on simulator sickness is that sickness does not occur from conflicting cues but rather from conflicting rest frames deduced from the various stimuli (Prothero, Draper, Furness, Parker, and Wells, 1999). When cues from the SRF do not correspond to the inertial rest frame cues, sickness can result. Since the brain chooses it's SRF based on what is perceived to be background, a key to reducing sickness might be to provide a suitable background that does not deviate from the inertial rest frame. The idea is not to remove all motion inducing cues but rather only those cues that indicate conflicting rest frames. Therefore, it might be possible to provide a stable reference frame in the background even though there is disagreement in cues being presented in the foreground. The result would be a reduction in the occurrence of sickness.

The term "independent visual background" (IVB) was given to stable background references that would be used to enhance the observers perception of the stable inertial frame of reference (Prothero, et al. 1997). The theory was put to test in a virtual environment by Prothero, et al. (1999). They used both see-through and occluded HMDs and presented a moving scene to their subjects. With the see-through HMD subjects were able to see a stable background wall which provided an IVB while the occluded HMD did not provide any IVB. Measurements of ataxia, SSQ, and vection ratings were collected and analyzed. The introduction of the IVB resulted in lower SSQ scores and less ataxia while not affecting vection ratings. A second, similar experiment added a task that required attention in the content of interest. Similar results were found except for no reduction in SSQ scores. The ataxia measures indicate there was a much reduced overall level of ataxia in the second experiment and therefore less opportunity for SSQ data to be effected by the experimental conditions. These results appear to confirm their hypotheses of the role of rest frames in simulator sickness and vection.

Additional studies have been completed to better understand the impact of IVBs and the characteristics of IVBs that have an impact on their effectiveness. Duh, Parker, and Furness (2001) conducted a study to evaluate the effects of an IVB on postural disturbance when presented with oscillating roll-axis stimuli at high (.8 Hz) and low (.05 Hz) frequencies. In this experiment they presented the IVB as an inertial-stationary grid that was superimposed over the rotating stumuli. They also evaluated the effects of the brightness of the grid with bright and dim IVB conditions. Their results confirm that an IVB reduced balance disturbance for the low frequency stimuli but not the high frequency stimuli. This result strengthens the theoretical underpinnings of the rest frame hypothesis. The visuo-vestibular conflict that is believed to result in simulator sickness is much more sensitive to the low frequency stimuli due to the high-pass characteristics of the vestibular system. The fact there was an impact seen for the low frequency stimuli indicates that an IVB in the form of a grid does indeed have an impact on how the brain determines which references to base evaluation of self-motion and self-orientation. The bright grid condition resulted in slightly reduced balance disturbance over the dim grid.

Duh, Abi-Rached, Parker, and Furness (2002) conducted another study to determine the effects of presenting an IVB in a stereo display. They manipulated the perceived depth of the grid with respect to the rotating stimuli. The grid was placed in front, about equal with, and behind the rotating stimuli. Again, there was confirmation that all presentations of the IVB resulted in reduced balance disturbance. However, there were no differences reported due to the varying depth of the grid. Duh, Parker, and Furness (2003) evaluated the effect of presenting an IVB in central vision, peripheral, vision or both. Their hypothesis that the IVB would have greater impact in the periphery did not hold up. In fact, subjects exhibited less balance disturbance when the IVB was presented in central vision. They surmise that while peripheral vision is of primary importance for determining self-motion and orientation it is not what the brain uses to identify and select the ideal rest frame. They indicate that the rest frame may be identified and monitored through different neural process than evaluation of self-motion.

Finally, a recent study was conducted to evaluate the effects of adding an IVB to a driving simulator. Lin, Abi-Rached, Kim, Parker, and Furness (2002) added several IVB “types” to a driving simulator and evaluated the resulting impact in simulator sickness. The IVB types included a grid, such as that used in the previous IVB studies, plus two natural reference frames made of either a few clouds or many clouds. They found that after two minutes of driving exposure, subjects reported lower SSQ scores were lower with the natural, cloud based IVB than with the grid. There was also a trend towards statistical significance where more clouds appear to reduce simulator sickness scores more then just a few clouds. This effect is likely due to the pronounced presence of the IVB caused by the additional luminance (the clouds were white) and area.

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